Tesla-Based Blood Pump and Its Applications

Choon-Sik Jhun

Ray Newswanger

Division of Artificial Organs,
Department of Surgery,
Penn State College of Medicine,
Hershey, PA 17033

Joshua Cysyk

Division of Artificial Organs,
Department of Surgery,
Penn State College of Medicine,
Hershey, PA 17033;
Department of Bioengineering,
Penn State University,
University Park, PA 16802

Branka Lukic

Division of Artificial Organs,
Department of Surgery,
Penn State College of Medicine,
Hershey, PA 17033

William Weiss

Gerson Rosenberg

Division of Artificial Organs,
Department of Surgery,
Penn State College of Medicine,
Hershey, PA 17033;
Department of Bioengineering,
Penn State University,
University Park, PA 16802

Introduction

A continuous-flow left ventricular assist device (LVAD) that Penn State University (PSU) has developed utilizes Tesla turbomachinery technology [1,2]. We recently tested the second version of the PSU Tesla LVAD; the size of the pump was significantly reduced while avoiding any degradation of hemodynamic and hemolytic characteristics. The primary goal of this study is to examine the (i) hydrodynamic performance and (ii) wall shear stresses on the volute and rotor. The secondary goal is design optimization in terms of the pump efficiency by varying design parameters such as (i) number of disks, (ii) disk gap spacing, and (iii) shape of the back cap (with or without a sharp fluid guider). Design iteration studies were performed at 6000 rpm and a range of flow rates from 2 to 8 lpm.

Materials and Methods

Pump Description. The pump consists of a suspended rotor that has 11 disks constructing the Tesla impeller. The most

distinctive feature of the PSU Tesla LVAD is the rotor suspension method: the rotor is passively suspended in the axial direction by the rotor and stator axial magnetic force and hydrodynamically in the radial direction. Figure 1 shows the second version of the PSU Tesla LVAD.

CFD Analysis. The Autodesk® Simulation CFD (Autodesk, Inc., San Rafael, CA) was used to predict the results of H-Q (pressure head-flow rate) obtained in vitro. The κ-ε turbulence model was employed based on the Reynolds number of the flow field through the pump.

Boundary Conditions. A constant pressure and flow were applied to the inlet and outlet, respectively. No-slip zero-flux boundary conditions were applied at the stationary walls.

Mesh Generation. The nominal grid contained approximately 1.6×10^6 points. Boundary mesh enhancement ensured at least three boundary layers to resolve the complex geometric details, such as the volute inlet, disk spaces, pin interfaces, and thin gap regions.

Computational Fluid Dynamics (CFD) Methodology. Time-varying analyses were performed. Incompressible Newtonian approximation for blood was employed with the fluid density of $1050 \, \text{kg/m}^3$ and viscosity 3.5 cP, respectively.

Mesh Refinement. The baseline mesh included 6.9×10^6 elements, and the refined mesh included 16.3×10^6 elements. On the refined mesh, the computations gave the pressure head increase of 1.5%.

Results

In Vitro Performance. H-Q from CFD and experiments were well comparable for all conditions.

Velocity Profile. Figure 2 shows the mean-velocity contours for the inflow and outflow at 8 l/min at 6300 rpm. As shown in our previous study, the tapered leading edge design reduced the fluid turning and mass flow through the disk gaps appeared to be uniformly distributed, i.e., the fluid power to each disk is evenly distributed (Fig. 2(a)). The jet flow at the exit of the blades and mean
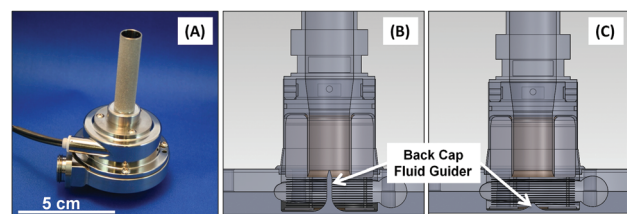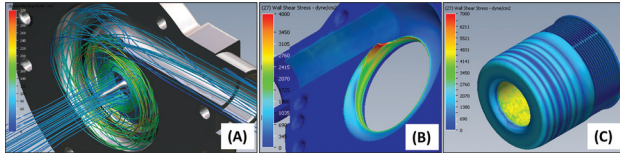

Fig. 1 (*a*) The second version of the Penn State Tesla LVAD. Cross section view with a long-fluid guider (*b*) and a short-fluid guider (*c*) on the back cap.
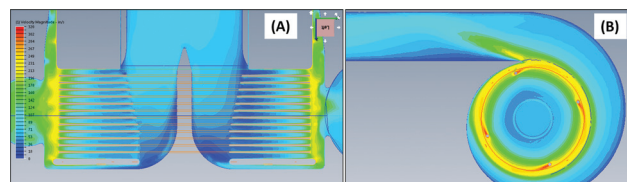
Fig. 2 Mean velocity profile through the (*a*) inlet, Tesla impeller, and (*b*) outlet

Fig. 3 (*a*) **Particle trace in fluid flow.** (*b*) **Wall shear stress at the volute.** (*c*) **Wall shear stress at the rotor.**

velocity trace of the pins are shown in Fig. 2(*b*). Reshaping the back-cap fluid guider has negligible effect on H; however, this reduced the recirculation region at the bottom backflow channel. Figure 3(*a*) shows particle traces in the fluid flow. Note that dominant fluid rotation occurs at the disks.

Wall Shear Stress. Figure 3(*b*) shows the wall shear stress on the volute surface. Relatively high wall shear stress ($\sim$500 Pa) was observed due to the jet flow. Figure 3(*c*) shows the wall shear stress on the rotor. The peak wall shear stresses are approximately 250 Pa and 500 PA, and appeared on the outer and inner surfaces of the rotor, respectively.

Design Parameter Studies. Design optimization studies were performed at 6000 rpm and flow rates from 2 to 8 lpm. Better efficiency was observed by increasing the number of disks and disk-gap spacing. Within our target in vivo operating range of 6–8 lpm, however, efficiency was not substantially affected by the gap spacing. It is unclear why the efficiency at 4 lpm with 11 disks was much higher than other flow conditions.

Discussion

A second version of the PSU Tesla LVAD was constructed and the performance was tested. The results compared favorably with the CFD results in all operating ranges. In our previous study on the first version, the peak shear stresses fall within the range of 300–500 Pa while the second version falls within 250–500 Pa at similar operating conditions. These values are high enough to potentially cause platelet activation; thus, further in vivo biocompatibility studies are necessary. The high stress regions are small, which should reduce the cellular exposure time, limiting the level of hemolysis. In fact, hemolysis studies have shown a satisfactory index of hemolysis over its operating range ($<$0.011 mg/dl). Design iterations revealed that the best efficiency was found to be 11 disks with 0.020" gap spacing. In summary, the PSU Tesla LVAD has the potential to become a lower cost device due to its ease of fabrication, flexibility of application, and suspension technology.

Acknowledgment

References

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